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HEAT STRESS IN CHEMICAL WARFARE CLOTHING

by

R. Farnworth and R.M. Crow

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B. Farnworth and R.M. Crow
Environmental Protection Section
Protective Sciences Division

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ABSTRACT

This paper presents an analysis of heat flow mechanisms which operate in a chemical warfare (CW) suit in order to estimate the extent to which it might be possible to alleviate heat stress without resorting to artificial cooling. The analysis uses Canadian, UK and US thermal and water vapour resistance measurements of CW materials/clothing and shows that little improvement in heat dissipation can be expected with material improvements alone. It is proposed that heat stress could be substantially reduced by making the CW suit with a minimal number of independent fabric layers and as close fitting as possible. Physiological tests are required to confirm the validity of this theory.

RÉSUMÉ

Ce document rend compte d'une analyse des mécanismes de flux thermique d'un costume de guerre chimique et permet d'évaluer jusqu'à quel point il serait possible de soulager l'accès de chaleur sans avoir recours à un procédé artificiel de refroidissement. Cette analyse se base sur des mesures canadiennes, britanniques et américaines de résistance thermique et d'étanchéité à la vapeur d'eau des tissus/vêtements de guerre chimiques. D'après cette analyse, lorsque seuls les tissus sont perfectionnés, on ne peut s'attendre qu'à une légère amélioration en termes de dissipation thermique. Il est suggéré que l'accès de chaleur pourrait être considérablement réduit si le costume de guerre chimique se composait d'un nombre minimal de couches séparées de tissu et s'il était aussi ajusté que possible. Il est nécessaire de procéder à des tests physiologiques pour confirmer la validité de cette théorie.

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INTRODUCTION

The recent trials in Australia (Tilley et al, 1981) have again underlined the perennial problem of heat stress of soldiers wearing chemical warfare (CW) clothing and equipment in a hot environment. These trials confirm the documented observations of earlier CW clothing field trials in the United States (Veatch) namely, that when soldiers wear CW clothing in a warm or hot environment, they feel hot.

Therefore, it is not surprising that, with the current state-of-the-art of CW clothing, the practical solution to heat stress, adopted by the UK and the US, is to have field commander's guides which outline the procedures for operating in a warm CW environment. Simply put, these guides point out the need to reduce work times and increase rest periods as the work rate increases, as the environmental conditions become warmer and more humid, and as the degree of CW protection is increased. The overall goal is to maintain, as best possible, a heat balance between how much heat is produced by the body and how much can be lost from it through the CW ensemble.

However, research continues to seek a possible solution to reducing the heat stress caused by CW clothing itself. Various approaches have been tried or suggested as how best to alleviate this heat stress. Over the years, the most significant and successful approach has been the introduction of a permeable rather than impermeable material for the CW overgarment. This permeable material allows heat to be lost by the evaporation of sweat, and, if the wind is blowing, by convection. However, further reduction in heat stress imposed by this permeable CW garment is still being sought.

The most practical and successful approach to date is auxiliary cooling. Goldman, 1981, has carried out laboratory studies on auxiliary cooling using water-cooled undergarments, an air-cooled vest, an ice-packets vest and a wettable cover. He found they all cooled the test mannequin to varying degrees. The first two approaches require power to circulate the water or the air, and would be appropriate where a person is linked to a vehicle such as a tank or aircraft (Kuehn et al, 1981) where auxiliary power is available. The last two approaches are power independent, but logistically complicated in that the ice-packets in the vest need re-freezing after relatively short periods of time, and the wettable cover needs a reliable supply of water.

Other solutions which have been either suggested or tried unsuccessfully are reducing the thickness of the charcoal-impregnated foam of the CW material system (USARIEM, 1981), using spacers under the CW garment to take advantage of the chimney effect of natural convection, the shingle construction of the garment to provide some ventilation and using the heat pipe principle to allow for heat exchange by convection.

In this paper we present the analysis of the heat flow mechanisms that operate in the suit without artificial cooling mechanisms in order to estimate the extent to which it might be possible to alleviate the heat stress problem without resort to such devices. The analysis is based on mannequin data for the US and UK CW suits, resistance measurements of the Canadian, UK and US CW suit materials, and straightforward theoretical considerations.

ANALYSIS OF HEAT FLOW

HEAT LOSS THROUGH THIN CLOTHING

Clothing layers may be characterized as either "thick" or "thin" depending on whether they derive their thermal insulation principally from the intrinsic resistance of the textile material and the air trapped within it or principally from the resistance of the air layer trapped between the textile layer and the skin or the textile layer beneath. The transition between thick and thin occurs at a thickness of the clothing layer of about 5 mm. Since even the charcoal foams are only 2 to 3 mm thick, all the components of the CW suit may be classified as "thin". Heat transfer through a set of clothing made up of several thin layers may be viewed as transfer across several trapped air layers each of a few millimetres thickness. Heat may cross such an air layer by one of two mechanisms: radiation or conduction. In air layers of 10 mm or less, convection may generally be discounted.

Radiative heat transfer rate (Q_{RAD}) across a space between two absorbing surfaces is governed by an equation of the form

$$\frac{Q_{RAD}}{\Delta T} = 4\sigma T^3 = 6 \text{ W/m}^2 \text{ K} \qquad [1]$$

which is independent of the thickness of the air layer. Here ΔT is the temperature difference across the space and σ is the Steffan-Boltzmann constant.

Conductive heat transfer rate (Q_{COND}) is given by

$$\frac{Q_{COND}}{\Delta T} = \frac{k_A}{X} \qquad [2]$$

where X is the thickness and k_A is the conductivity of air (0.025 W/m K). For a 5 mm thick air layer we have

$$\frac{Q_{COND}}{\Delta T} = \frac{.025}{.005} = 5 \text{ W/m}^2 \text{ K}$$

The radiative and conductive heat transfer rates are of roughly the same size. In addition to air layers trapped within clothing, there is always a few millimetres-thick still air layer adhering to the outermost surface, the exact thickness depending on windspeed or body motion. Heat can be viewed as travelling across this layer in the same way as across internal air layers and then being dispersed throughout the atmosphere by convection.

A simple, approximate, scheme for the calculation of heat transfer across several layers of clothing is to use equation [2] for the conduction with X representing the total thickness of all layers and replace equation [1] by

$$\frac{Q_{RAD}}{\Delta T} = \frac{4\sigma T^3}{n+1} = \frac{6}{n+1} \text{ W/m}^2 \text{ K} \qquad [3]$$

where n is the number of fabric layers. (Equation [3] is valid for air spaces of equal thickness.)

Heat may be lost due to the evaporation of sweat from the skin and its diffusion out through the clothing. Again, for thin layers of air, convection is unimportant. The rate of outward diffusion depends on the difference in vapour pressure between the skin and the ambient air (ΔP) and the total vapour resistance of all layers of air and fabric (R_v). The heat loss, Q_{EVAP}, is the rate of diffusion times the latent heat of vaporization of water ($H = 2.4 \times 10^6$ J/kg)

$$Q_{EVAP} = \frac{H \Delta P}{R_v} \qquad [4]$$

For an air layer of thickness X

$$R_v = \frac{X}{k_v} \qquad [5]$$

where k_v is the "vapour conductivity of air" (essentially the diffusion constant but the units are different), $k_v = 1.8 \times 10^{-10}$ kg/s m Pa. For a layer of textile, the diffusion constant is somewhat lower, though not dramatically so, unless the fabric is coated.

The water vapour resistance of the textile fabrics making up the US and Canadian CW suits and of the actual UK and US CW suits have been measured using the methods described in the EAG-14, 1982 report.

ANALYSIS OF AVAILABLE DATA

UK Suit

The UK system consists of four layers (combat clothing and liner, charcoal layer and outer) having a total thickness of 2.4 mm and a total water vapour resistance equivalent to 6.2 mm of air as measured at DREO. These figures refer to the fabrics alone, without air layers. The water vapour resistance of the complete suit (EAG-14, 1982) is 1.0×10^8 m^2 Pa s/kg, equivalent to 18 mm of still air. Clearly there are air layers contributing to the total resistance. From these figures the overall thickness of the suit may be estimated to be 14.2 mm.

From the overall thickness and the number of layers we may estimate the thermal resistance of the suit to be 0.34 m^2 K/W. The value quoted by the UK is 0.30 m^2 K/W. For such a simple-minded calculation, the agreement is essentially perfect. The UK suit can therefore adequately be described as a system of four thin fabric layers with air layers totalling 12 mm thickness, when the suit was tested on the mannequin.

US Suit

The foam and outer fabric of the US system have a combined thickness of 2.8 mm and a water vapour resistance equivalent to 5.1 mm of still air as measured at DREO. The reported water vapour resistance of the ensemble with and without fatigues underneath are both 36 mm equivalent still air (EAG-14, 1982). Thus the ensemble thickness is estimated to be 33 mm. Taking three layers for the suit with fatigues and two without, the expected thermal resistances are 0.44 and 0.36 m^2 K/W. The US quote 0.40 and 0.33 m^2 K/W respectively. Again the agreement is good.

We note that with the US suit the overall thickness of the ensemble is about 33 mm with or without the fatigues underneath. Thus it appears that the suit takes on its own form and the man fits inside leaving an airspace determined by the difference between his radius and the suit's. (Rather like a man in a barrel.) This is quite likely true of the UK and Canadian suits as well.

Canadian Suit

The Canadian suit, foam plus outer shell fabric, has a combined thickness of 2.7 mm and a water vapour resistance equivalent to 5.3 mm of still air. No data on the water vapour resistance of the complete clothing assembly are available.

Intrinsic Thermal Resistance of CW Shell Fabrics

The thermal resistance of the Canadian, US and UK charcoal-impregnated layers are, respectively, 0.068, 0.068 and 0.041 m^2 K/W. The intrinsic thermal resistance of the shell fabrics used over these layers is too small to be measured or to be of consequence. These thermal resistances are of the order of 15% of the total and so are of minor significance.

Conclusion

For the purposes of determining heat stress, the above data demonstrate that the materials of the Canadian suit are identical to those of the US and differ from those of the UK only in the number of layers. It is the thickness of the total assembly that determines heat stress, i.e. it is the fit of the suit and its overall design that counts, not the properties of the materials.

Given that fit is critical, it is not clear how seriously the US and UK dummy-measured values of thermal or vapour resistance can be taken. Did the suits used in the trials fit the dummy or the test subjects properly? Do the suits fit the people who will have to suffer in them, properly? The UK suit seems a better fit but is this typical?

HEAT STRESS AND TOLERANCE TIME

Once thermal and vapour resistances of the materials are known it is a fairly straightforward matter to calculate the maximum heat flow possible through the suit to an accuracy of the order of 20%. The results of such a calculation using the US resistance data are shown in Figure 1.

A man engaged in moderate work, walking at 5 km/h for example, will produce of the order of 300 W of heat that must be dissipated if he is to remain thermally neutral. If he sweats profusely, he may dissipate heat at the required rate at about 0°C. A sedentary man produces about 150 W. He may remain thermally neutral at about 25°C, this more or less depending on the humidity.

Only one experiment has been done on heat stress in the Canadian CW suit (Nolan). At 20°C 75% RH the heat storage rate was about 70 W. The heat production in this experiment (not measured) was probably in the range of 200 to 300 W. Therefore the heat dissipation rate was of the order of 130 to 230 W. The value predicted by the theoretical calculation is 155 W. (The calculated value is probably on the low side because the effect of wind is omitted and the experiment did have some wind blowing on the test subjects.)

To help put these data in perspective, Figures 2 and 3 show tolerance times for 300 W and 150 W activity based on a tolerable heat storage of 100 watt hours. It should be observed, however, that while tolerance times may be useful as heuristic aids in discussions of the severity of the heat stress problems, they are of little value as measures of the relative merits of various suits. The problem is that tolerance times depend on the difference between heat production and heat loss rates, a quantity that may be very much less than both and so is very sensitive to small fluctuations or errors in either.

Physical or physiological determinations of clothing resistances can rarely be trusted to an accuracy of better than 10% and are often much worse. Also, work rates or heat production rates are highly variable from individual to individual and can therefore never be predicted with accuracy. Suppose a man is working at 360 W and has a heat dissipation of 300 W, and suppose both of these quantities are uncertain to 10%. The net heat storage may be as low as zero or as high as 90 W. Thus his tolerance time may be infinite or as short as one hour.

The use of tolerance times as relative measures of the worth of CW suits will grossly exaggerate the differences among them, and apparently

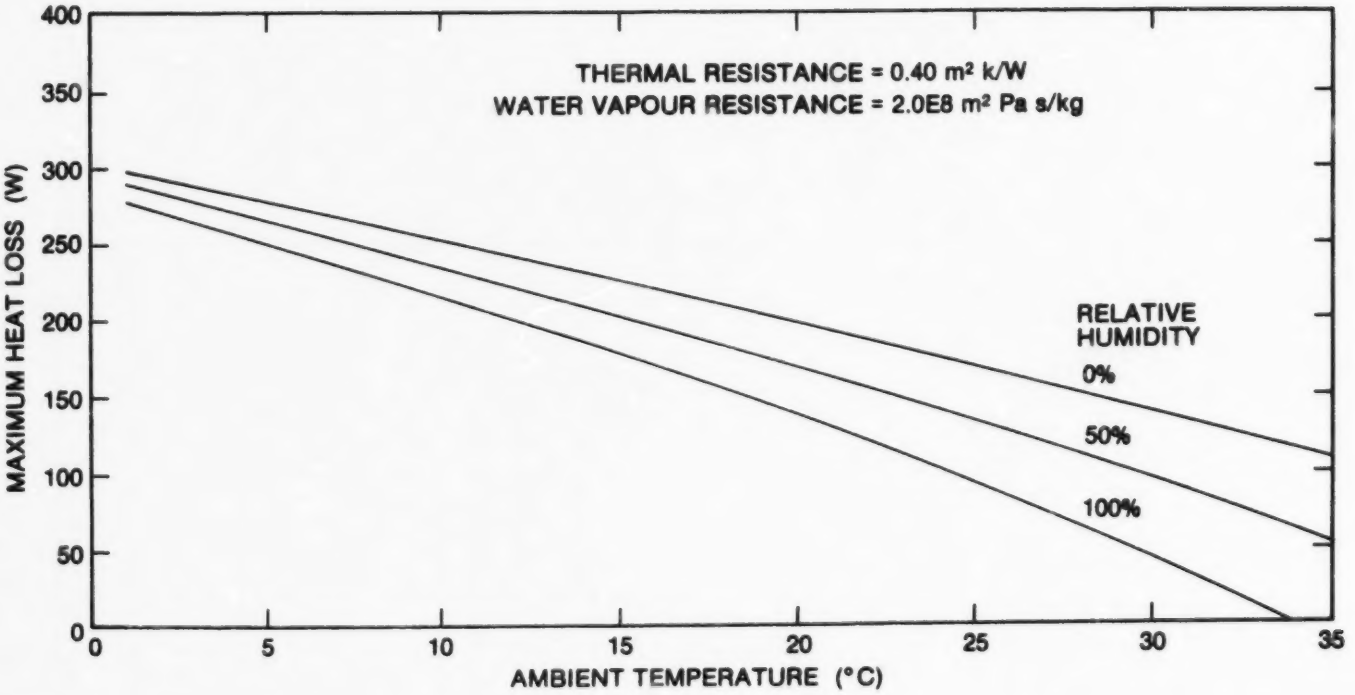

Figure 1: Maximum heat loss at various temperatures and humidities using US resistance data.

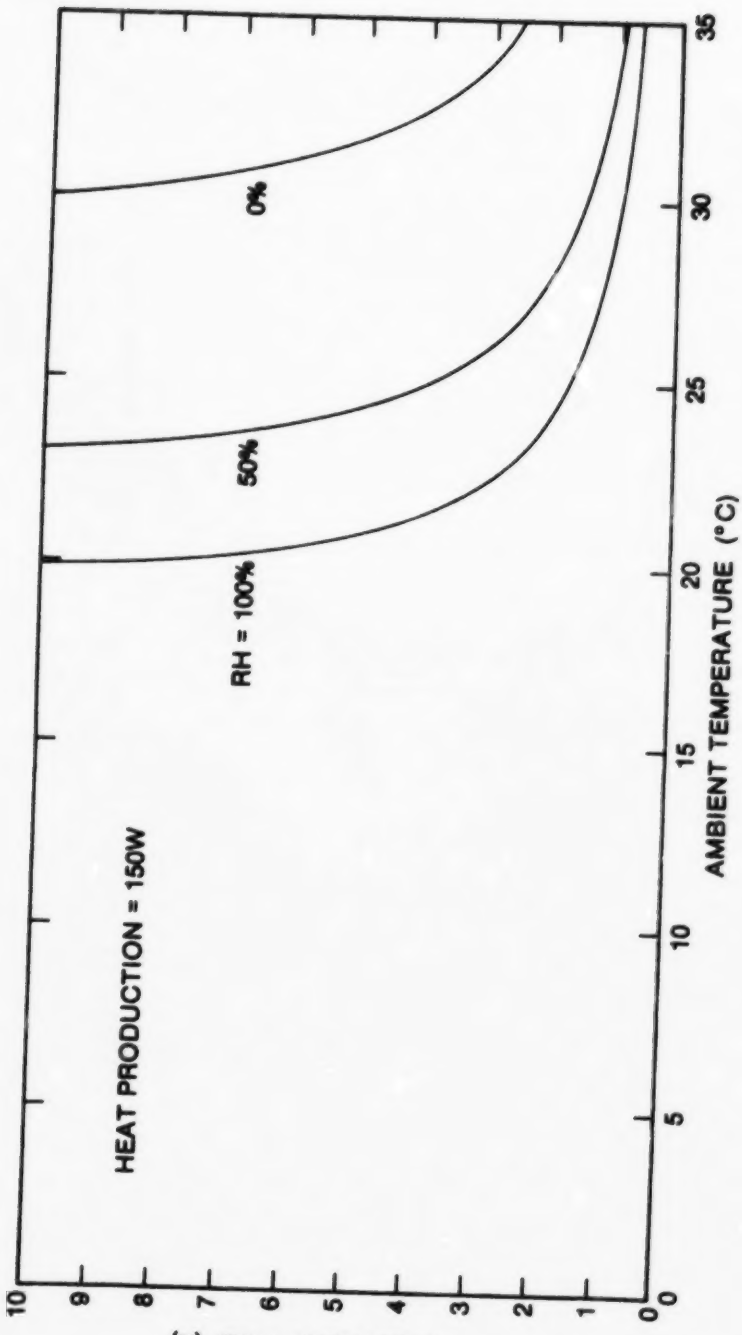

Figure 2: Tolerance times at various temperatures and humidities for a heat production rate of 150 W using US resistance data.

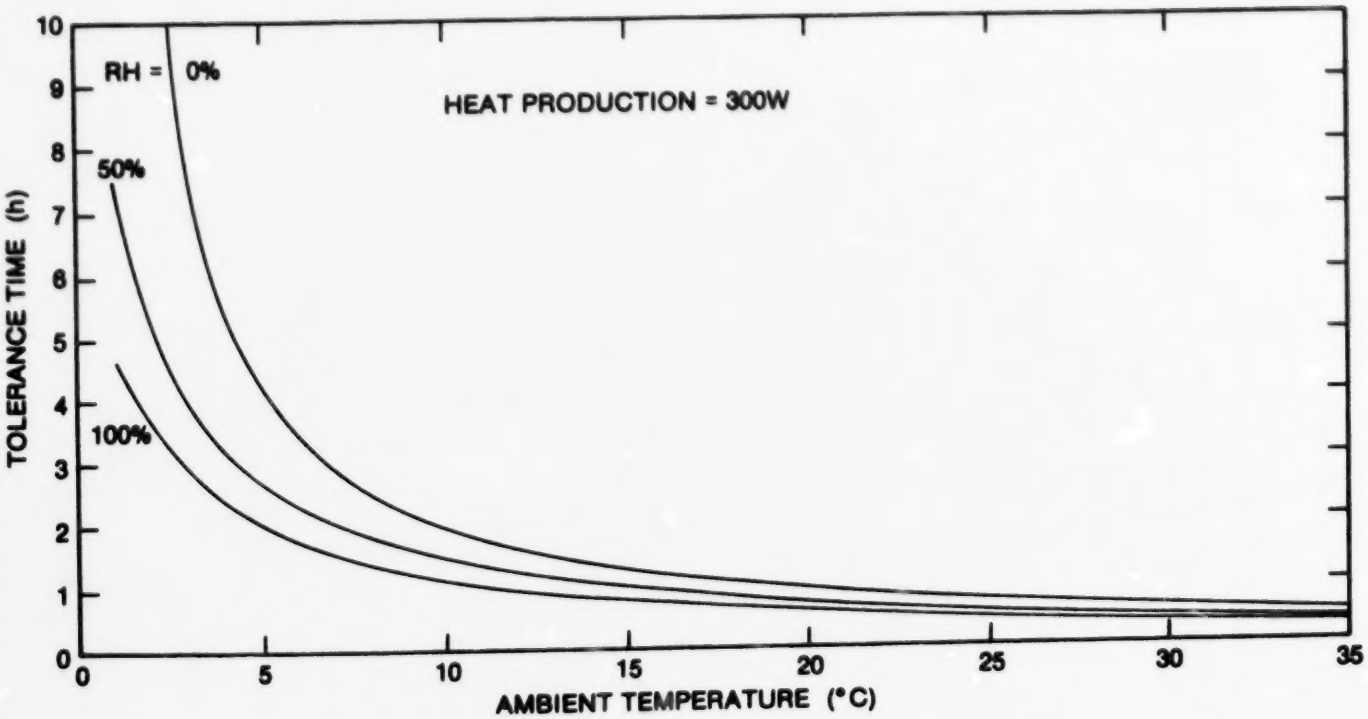

Figure 3: Tolerance times at various temperatures and humidities for a heat production rate of 300 W using US resistance data.

large differences may in fact be due to small experimental errors and have no basis in reality.

Even if one could predict or measure tolerance times accurately, they would still require careful interpretation. It is by no means clear how work rates are set under field conditions. Do soldiers work as hard as is necessary or as hard as their clothing will allow? If the former, then tolerance times would be appropriate measures of performance; if the latter, only work rates are appropriate. Obviously, tolerance times are as sensitive to small changes in temperature as they are to changes in work rates and can probably never be reliably predicted for field conditions.

It should be obvious from Figure 3 that the heat stress problem in a CW suit is not merely a minor inconvenience but a major handicap to all but the most sedentary of personnel. To permit a man to work hard in a CW suit (at say 600 W), would require a decrease in thermal and vapour resistances of the order of a factor of 2 at 0°C and of a factor of 10 at 30°C and high humidity. In light of this massive problem, the differences among the CW assemblies of the various nations are utterly insignificant.

ADDITIONAL HEAT FLOW MECHANISMS

The discussion preceding has neglected various factors that may be important under some circumstances.

The resistances of the suit may be substantially reduced by wind. This can be the result of three effects:

a. Stripping off of the outermost air layer;

b. Penetration of the outermost layer and disruption of inner air layers;

c. Pressing of the fabric layers together, eliminating the inner air layers.

Of the three, only the first is certain to occur. The influence of the other two is by and large unknown.

The calculations also neglected solar radiation which can only heat and may hurt personnel substantially since it may contribute a possible heat influx of the order of hundreds of watts.

It is possible that heat flow may be improved by the influence of body motion. Air may be pumped in and out of the clothing with each step, the so-called "bellows ventilation".

Our (very incomplete) knowledge of bellows ventilation, so far, indicates that it is difficult to design the clothing to give any substantial effect. This view is reinforced by the UK experience that there is very little difference in heat stress between open and closed configurations. Since bellows ventilation is of interest in connection with Arctic clothing, it is the subject of continuing investigation at DREO.

These three effects are of interest under specific conditions but they are not of general importance and should be considered as secondary to the main question.

POSSIBLE SOLUTIONS

Apart from the auxiliary cooling systems mentioned earlier, the only way to reduce heat stress is to limit work rates or to reduce the thermal and vapour resistances of the suit. Severely limiting work rates would be, in effect, hobbling the army and, in any case, is unlikely to be possible in a real battle.

One is left, apparently, only with the option of reducing thermal and water vapour resistances. Since most of each resistance is caused by the air layers, it is essential that these be eliminated first. There is no point in trying to reduce the resistances of the fabric layers themselves as long as they form only a minor portion of the total resistances. By leaving the materials unchanged, but eliminating the air layers, it should be possible to reduce the thermal resistance of the suit to about 0.2 m^2 K/W and the vapour resistance to about 1.0×10^8 m^2 Pa s/kg (18 mm equivalent still air), i.e. by about a factor of 2.

CONCLUSIONS

It is apparent from the simple analysis presented here that the materials employed in the current UK, US and Canadian CW suits are of sufficiently low thermal and water vapour resistances that little improvement in heat dissipation can be expected with material improvements alone. Certainly, reduction of heat stress will require changes in the design of the suit either to reduce heat and vapour resistances or to incorporate some auxiliary cooling. If the resistances are to be lowered, the air layers

trapped within the clothing must be reduced in number and thickness, i.e. the suit should be of the minimum number of independent fabric layers and be as closely fitting as possible.

A series of physiological tests with specially constructed close-fitting suits is proposed in order to confirm this analysis.

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